Overview of the Testing of a Small-Scale Proprotor

Larry A. Young
NASA Ames Research Center
Moffett Field, CA

Earl R. Booth, Jr.
NASA Langley Research Center
Hampton, VA

Gloria K. Yamauchi
NASA Ames Research Center
Moffett Field, CA

Gavin Botha
NASA Ames Research Center
Moffett Field, CA

Seth Dawson
The Boeing Company
Mesa, AZ

Summary

This paper presents an overview of results from the wind tunnel test of a 1/4-scale V-22 proprotor in the Duits-Nederlandse Windtunnel (DNW) in The Netherlands. The small-scale proprotor was tested on the isolated rotor configuration of the Tilt Rotor Aeroacoustic Model (TRAM). The test was conducted by a joint team from NASA Ames, NASA Langley, U.S. Army Aeroflightdynamics Directorate, and The Boeing Company. The objective of the test was to acquire a benchmark database for validating aeroacoustic analyses. Representative examples of airloads, acoustics, structural loads, and performance data are provided and discussed.

Nomenclature

C_P	Rotor power coefficient
C_T	Rotor thrust coefficient
FM	Rotor hover figure of merit
M_{tip}	Rotor tip Mach number
R	Rotor radius
x/R	non-dimensional tunnel longitudinal coordinate, origin at hub, positive downstream
y/R	non-dimensional tunnel lateral coordinate, origin at hub, positive on rotor advancing side
z/R	non-dimensional tunnel vertical coordinate, origin at hub, positive up
V	Wind tunnel test section velocity
α_s	Rotor shaft angle, deg, shaft vertical at zero degrees angle, positive aft

Presented at the American Helicopter Society 55th Annual Forum, Montreal, Canada, May 25-27, 1999.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **1999**	2. REPORT TYPE	3. DATES COVERED **00-00-1999 to 00-00-1999**
4. TITLE AND SUBTITLE **Overview of the Testing of a Small-Scale Proprotor**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Army/NASA Rotorcraft Division,Army Aviation and Missile Command,Aeroflightdynamics Directorate (AMRDEC), Ames Research Center,Moffett Field,CA,94035**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Presented at the American Helicopter Society 55th Annual Forum, Montreal, Canada, May 25-27, 1999

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**12**	

μ	Advance ratio, $V/\Omega R$
η	Proprotor efficiency, $C_T\mu/C_P$
ψ	Rotor azimuth, deg.
Ω	Rotor rotational speed, rad/s

Introduction

The successful introduction of civil tiltrotor aircraft is dependent in part on identifying and reducing, or suppressing, the noise generation mechanisms of tiltrotor aircraft proprotors. To accomplish these goals, a series of wind tunnel tests with a new generation of tiltrotor models is required. The purpose of the Tilt Rotor Aeroacoustic Model (TRAM) experimental program is to provide data necessary to validate performance and aeroacoustic prediction methodologies and to investigate and demonstrate advanced civil tiltrotor technologies. The TRAM project is a key part of the NASA Short Haul (Civil Tiltrotor) (SH(CT)) program. The SH(CT) program is an element of the Aviation Systems Capacity Initiative within NASA. Reference 1 summarizes the goals and objectives and the overall scope of the SH(CT) program.

The current scope of TRAM experimental investigations is focused on the following:

1. Acquisition and documentation of a comprehensive isolated proprotor aeroacoustic database, including rotor airloads.

2. Acquisition and documentation of a comprehensive full-span tiltrotor aeroacoustic database, including rotor airloads, to enable assessment of key interactional aerodynamic and aeroacoustic effects by correlating isolated rotor and full-span TRAM wind tunnel data sets with advanced analyses.

3. An advanced technology demonstrator test platform for low-noise proprotors.

The first wind tunnel test of the TRAM project was an isolated rotor test in the Duits-Nederlandse Windtunnel (DNW) in The Netherlands (Fig.1). This isolated rotor test was the first comprehensive aeroacoustic test for a tiltrotor proprotor, including not only noise and performance data, but airload and wake measurements as well. The TRAM isolated rotor test stand was installed and tested in the DNW open-jet test section during two tunnel entries, in December 1997 and April-May 1998.

Fig. 1. TRAM Isolated Rotor Configuration in the Duits-Nederlandse Windtunnel (DNW) in The Netherlands

This paper provides an overview of the data acquired during the TRAM DNW test. Follow-on plans for the full-span (dual-rotor, complete airframe) TRAM will be briefly discussed.

Description of Model and Wind Tunnel Facility

A general description of the TRAM isolated rotor configuration is found in Reference 2. A description of the DNW and its rotary-wing test capability is found in Reference 3. The model proprotor tested on the TRAM isolated rotor test stand was a 1/4-scale (9.5 ft diameter) V-22 rotor. The rotor was counterclockwise rotating

(planform view over the rotor); i.e., it was a right-hand side or starboard rotor. The isolated proprotor was tested in the 8x6m open-jet test section of the DNW. The 1/4-scale V-22 proprotor was tested at reduced tip speed of 0.63 tip Mach number because of operational considerations (the nominal design tip speed of the V-22 Osprey aircraft is M_{tip} = 0.71). All airplane-mode proprotor data were acquired at 0.59 tip Mach number (equivalent to that of the V-22 aircraft).

The TRAM isolated rotor test stand was comprised of two major elements: the rotor and nacelle assembly and the motor mount assembly. The rotor and nacelle assembly was attached to the acoustically treated isolated rotor test stand at a mechanical pivot or 'conversion axis' (fig. 4). This conversion axis allowed the nacelle to be manually rotated (in between tunnel runs) in 5 degree increments from airplane to helicopter modes. An electric motor provided power to the rotor via a super-critical driveshaft. Rotor shaft angle changes were accomplished in flight with the DNW sting, which automatically maintained the hub on tunnel centerline. All rotating data channels were amplified by a Nationaal Lucht-en Ruimtevaartlaboratorium (The Netherlands National Aerospace Laboratory, NLR) developed Rotating Amplifier System (RAS) to enhance transducer signal to noise ratios before entering the slipring (reference 4).

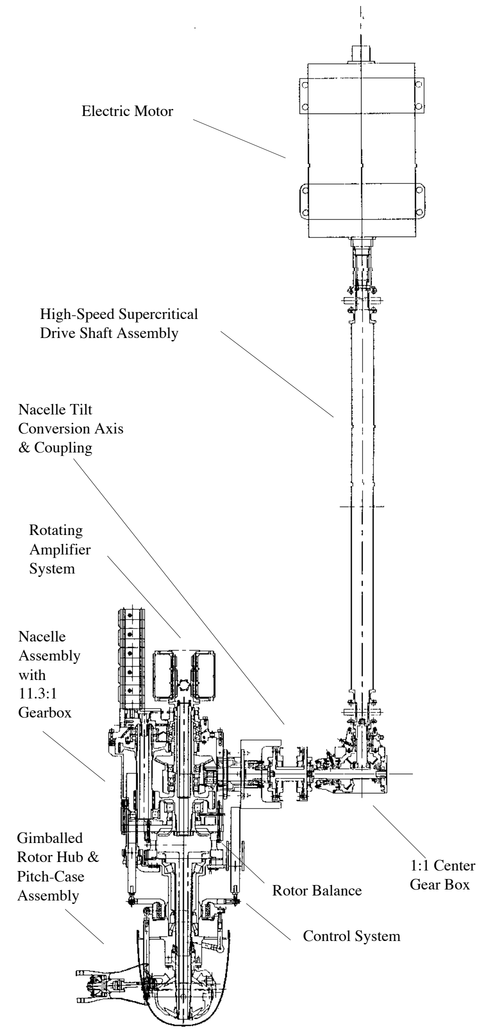


Figure 4 -- Isolated Rotor Configuration (Planform View With Nacelle Assembly Positioned in Airplane-mode)

A more detailed summary of the characteristics of the TRAM isolated rotor test stand and the 1/4-scale V-22 rotor is noted below:

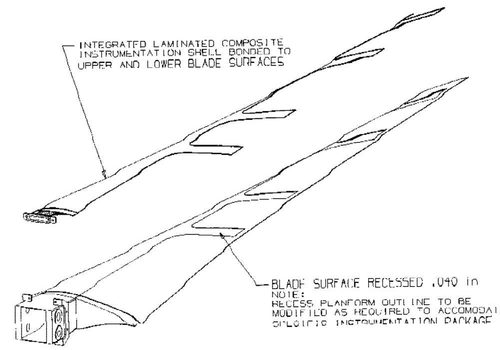
- TRAM Isolated Rotor Configuration Description (Fig. 4)
  - Test stand is wind tunnel sting-mounted; compatible with DNW and National Full-scale Aerodynamics Complex (NFAC) stings
  - Drive train designed for nominal 300 HP and 18,000 RPM motor; employs

one right-angle 1:1 gearbox and a 11.3:1 gear reduction transmission

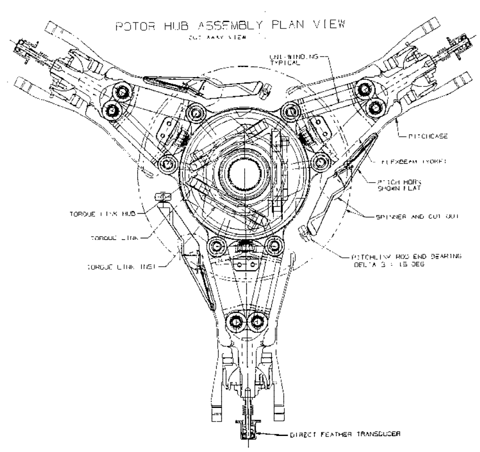
- Nacelle tilt/incidence angle (about the 'conversion axis') is ground adjustable
- Six-component rotor balance and instrumented torque coupling (with primary and secondary measurements)
- 300-ring slip ring and rotating amplifier system
- Three electromechanical actuators and a rise-and-fall swashplate; rotating and nonrotating scissor sub-assembly design allows full proprotor collective/cyclic ranges without changing hardware
- rotor control system and console designed to minimize re-rigging between different operating regimes
- Self-contained model utilities within nacelle and motor-mount assemblies
- Motor-mount acoustically treated with foam panels
- Nacelle assembly not acoustically treated but geometrically scaled for V-22 aircraft outer mold
- Model capable of being tested to full V-22 operating envelope
- Rotor shaft interface hardware designed to easily install and test advanced proprotors on TRAM test stands
- Isolated rotor configuration is hardware compatible with the full-span model; hardware is shared between the two test stands

• Rotor Characteristics and Instrumentation (Fig. 5)

- Gimballed rotor hub with constant velocity joint (spherical bearing and elastomeric torque links)
- Rotor hub is dynamically and kinematically similar to V-22 aircraft hubs
- 1/4-scale V-22 rotor set with both strain-gauged and pressure-instrumented blades
- Rotor pressure-instrumentation consists of 150 transducers (three different types of Kulite transducers) distributed over two rotor blades
- High fidelity scaling with respect to the V-22 rotor for blade/airfoil contours
- First elastic modes (flapwise, chordwise, and torsional) of blades dynamically scaled to V-22 frequencies
- Both strain-gauged and pressure-instrumented blades have nominally identical mass distributions and CG locations
- Adequate instrumentation provided to acquire a good blade/hub structural load data set for analytical correlation.



(a)



(b)

Fig. 5a-b TRAM 1/4-scale V-22 Rotor (a. Blade and b. Hub)

Test Description

Two tunnel entries were conducted in the DNW wind tunnel with the TRAM isolated rotor test stand and the 1/4-scale V-22 rotor. The first tunnel entry was in December 1997 and it was focused on TRAM test stand risk reduction and envelope expansion for the 1/4-scale V-22 rotor. The second entry in April-May 1998 was devoted to acquiring a high quality isolated rotor aeroacoustic database for the SH(CT) program.

The German Dutch Wind Tunnel (DNW) is located in Emmeloord in The Netherlands. It is a world-class acoustic wind tunnel facility that has been used for several important international rotorcraft acoustic test campaigns since it became operational in the late 1970's. NASA and the U.S. Army have previously conducted joint helicopter acoustic tests in the DNW. Like many of these previous tests, the U.S. Army enabled access to the DNW facility for the TRAM isolated rotor acoustic test.

The DNW test focused mostly on low-speed helicopter-mode test conditions. The test objective priorities were in order of importance: detailed acoustic survey of Blade Vortex Interaction (BVI) phenomena in helicopter-mode descent; broadband noise in hover and low-speed helicopter-mode flight; parametric trend data (as a function of α_s, μ, M_{tip}, and C_T) on helicopter-mode acoustics; airplane-mode performance and acoustic measurements; transition flight performance and loads measurements. Because of time and load limit constraints, transition flight ($-15 < \alpha_s < -75$ degrees) measurements were not made. Data was acquired to meet all other test objectives.

The TRAM isolated rotor test stand, as earlier noted, was mounted on the DNW sting. The DNW sting is articulated to allow for not only angle of attack sweeps but beta/yaw angle and vertical sting translation sweeps as well. This sting articulation capability proved to be very useful during the successful execution of the test program. The TRAM test stand was positioned inside the open-jet test section of the DNW. The outer (outside the tunnel flow) containment of the test section was acoustically treated with foam fairings. A DNW-provided acoustic traverse was positioned underneath the model for acoustic measurements during the test. The DNW also provided laser and associated equipment to make laser-light-sheet flow visualization and particle image velocimetry measurements during the TRAM test.

Proprotor Performance

Rotor performance measurements were made during the DNW test with the TRAM six-component rotor balance and an instrumented (torque and residual thrust) flex-coupling (see figure 2).

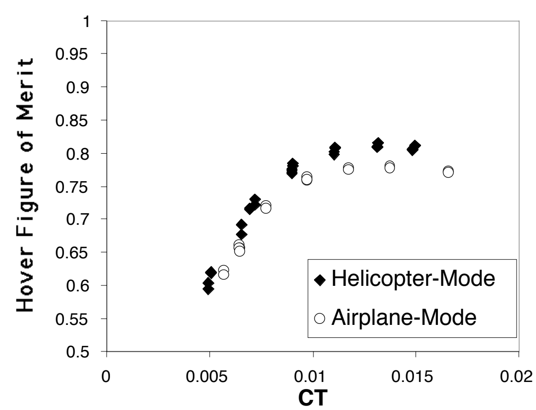


Fig. 2 Hover Figure of Merit (M_{tip}= 0.63)

The 1/4-scale V-22 TRAM figure-of-merit data compares reasonably well with data from a large-scale proprotor hover test at NASA Ames Research (Reference 5). No Reynolds number corrections have been made for the above data points. The two sets of data (airplane- and helicopter-mode) reflect the two configurations for which hover data was taken. (Helicopter-mode is when the nacelle incidence angle with respect to the motor-mount assembly and DNW sting axis is 75 degrees (near perpendicular) and airplane-mode is when the nacelle incidence angle is zero degrees.) Because of body interference effects from the TRAM test stand motor-mount sub-assembly, it is not surprising to note a fairly substantial impact on hover figure

of merit for the ‘helicopter-mode’ versus the ‘airplane-mode’ configurations.

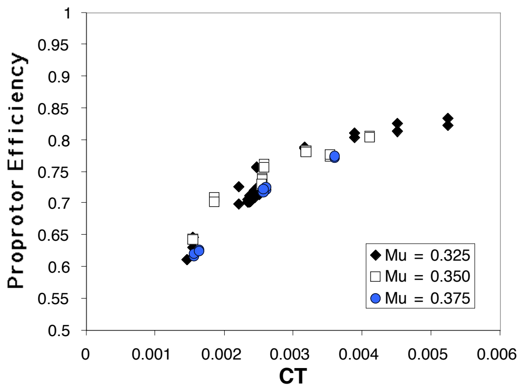


Figure 3 – Airplane-Mode, Low-Speed Cruise, Proprotor Efficiency (M_{tip}= 0.59)

Figure 3 summarizes low-speed airplane-mode proprotor efficiency data acquired during the test. A clean spinner fairing aerodynamic tare was applied to the data in figure 3. This performance data was acquired at the V-22 aircraft’s airplane-mode tip mach number (M_{tip}=0.59) and for μ=0.325, 0.35, and 0.375. The data was acquired for the maximum practical open-jet tunnel velocity, where the test section flow field was still reasonably steady. Both primary and secondary rotor balance measurements are shown in the figure. The proprotor efficiency trends measured are comparable to performance data from previous tests (reference 6). The 1/4-scale V-22 TRAM DNW test results, though, will greatly augment this extremely limited airplane-mode cruise performance data set in the literature.

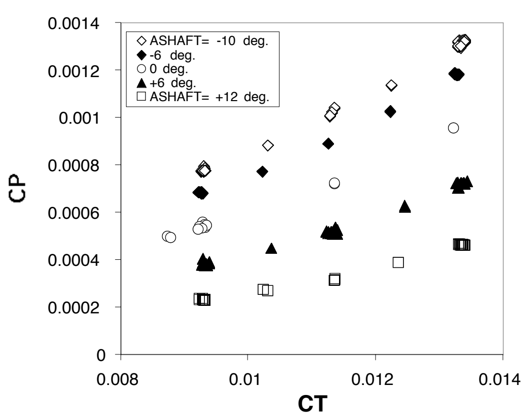


Fig. 4 Helicopter-Mode Power Polar (M_{tip}=0.63)

Figure 4 shows a power polar in helicopter-mode forward-flight for an advance ratio of μ=0.15 and shaft angles ranging from α_s= -10 to +12 degrees. This is only a small subset of the data acquired during the DNW test. Hub/spinner aerodynamic tares were applied to the figure 4 performance data. The 1/4-scale V-22 data is consistent with full-scale XV-15 helicopter-mode isolated rotor test results at NASA Ames Research Center (Reference 7); power polar trends are in general agreement, given the differences between rotor solidity and scale between the two tests. However, the 1/4-scale V-22 performance data is far more comprehensive in terms of the C_T and rotor shaft angle sweeps performed.

Rotor Structural Loads and Trimmed Control Settings

The TRAM rotor had a strain-gaged blade for safety-of-flight monitoring and blade structural load measurement. Rotor trim (for zero gimbal angle) control settings as a function of rotor shaft angles and tunnel speed were also measured.

Figure 5 shows representative data for the rotor control trim settings for cyclic pitch for the 1/4-scale V-22 rotor in helicopter-mode flight. The rotor was trimmed for zero one-per-rev gimbal angle. The cyclic pitch measurements were derived from the nonrotating control actuator stroke positions, given the kinematic control system equations. The general trend for the 1/4-scale cyclic pitch trim settings is consistent with previous test results for proprotors in low-speed helicopter-mode forward-flight (reference 7).

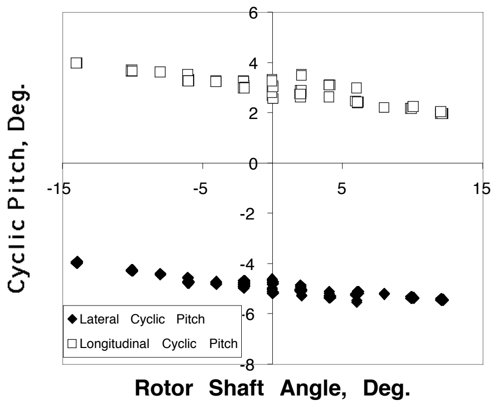
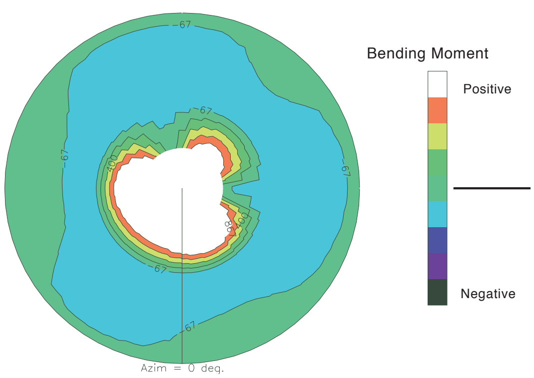
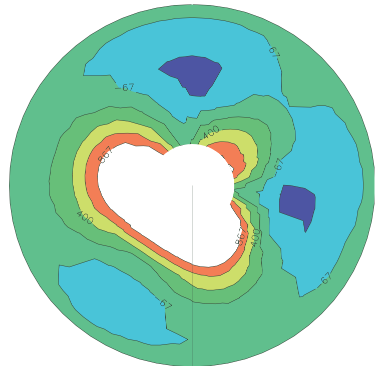


Figure 5 – Rotor Cyclic Pitch Trim Settings (μ=0.15 and C_T=0.009)

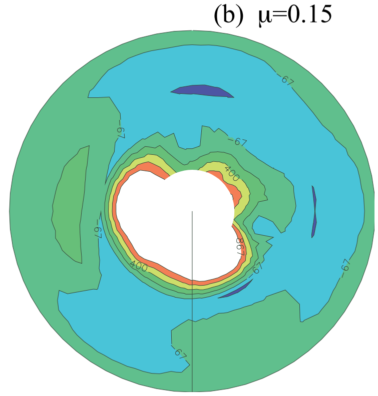
Figure 6a-d is a sample set of contour plots for the rotor flap bending loads. The redistribution of the flap bending moments across the rotor disk can be seen as the tunnel advance ratio increases from μ = 0.125 (Fig. 6a) to 0.20 (Fig. 6d). Other structural load data were acquired during the DNW test, including blade chord bending moment and torsional loads and pitchlink, pitch-case, and flexbeam loads. The data will be used to validate a new generation of comprehensive aeromechanics analysis codes.



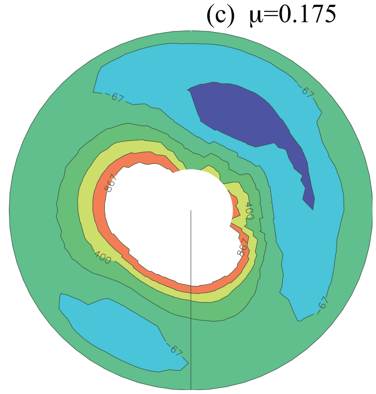
(a) μ=0.125



(b) μ=0.15



(c) μ=0.175



(d) μ=0.20

Fig. 6a-d -- Flap Bending Moments for Helicopter-Mode Flight (C_T=0.013 and α_s= -2 deg.)

Acoustics

Among the most crucial information acquired during the TRAM DNW isolated rotor test was the acoustic data from the 1/4-scale V-22 rotor. The TRAM test stand and DNW acoustic traverse are shown in figure 7.

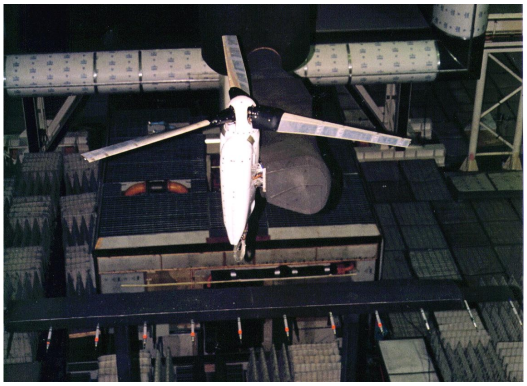


Fig. 7 TRAM Isolated Rotor Configuration and the DNW Acoustic Traverse

Acoustic data were acquired using a combination of in-flow traversing and out-of-flow fixed microphones. Thirteen microphones were equally spaced from -1.86 y/R to 1.86 y/R on a traversing microphone wing (also shown in figure 7). In addition, two microphones were placed outside the test section flow, one above the model and another located adjacent to the hub on the advancing side of the rotor. Piston-phone calibrations, background noise measurements, and installed model reflection tests were performed.

For each rotor test condition, the rotor hub height was maintained constant while the hub longitudinal location was allowed to change with shaft angle. The microphone wing was traversed along a plane 1.73 z/R beneath the center of the rotor hub from -2.76 x/R to 2.76 x/R, centered on the actual rotor hub x-location for the test condition. At seventeen equally spaced locations, the traversing microphone wing motion was stopped and data was acquired.

Figure 8 is a representative contour plot of the Blade Vortex Interaction Sound Pressure Level (BVISPL) acoustic survey measurements in helicopter-mode operation. Prominent in figure 8 is the BVI 'hot spot' on the advancing-side of the rotor.

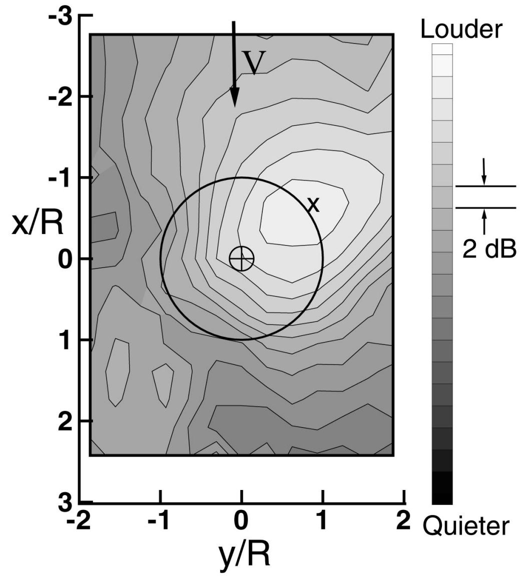
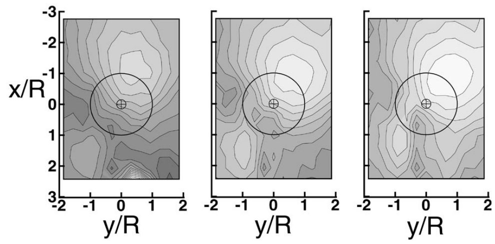


Fig. 8 -- Acoustic Survey of Proprotor in Helicopter-Mode (BVI Descent Condition)

The general characteristic of the 1/4-scale V-22 acoustic survey is similar to 0.15-scale JVX rotor results reported in reference 8 and full-scale XV-15 results in reference 9. However, the 1/4-scale V-22 data from the DNW test is unique in its scope (in terms of test envelope and acoustic parametric trends measured), its quality (with respective to the tunnel flow and acoustic characteristics), and its comprehensiveness (with respect to the number and types of aeroacoustic, aeromechanic, and rotor wake measurements made). The acoustic results from the 1/4-scale V-22 DNW test will improve the understanding and reduction of tiltrotor BVI noise which is important for civil tiltrotor passenger and community acceptance.

Acoustic data were acquired for a range of advance ratios (μ=0.125, 0.15, 0.175, 0.2), rotor shaft angles (α_s= -14 to +12 degrees), and thrust sweeps (C_T=0.009 to 0.014) were investigated. A detailed and comprehensive discussion of the 1/4-scale V-22 TRAM acoustic results will be found in reference 10. One example of the BVISPL acoustic trend with increasing μ, for constant α_s and C_T, is presented in figure 9. As would be expected, the maximum noise levels increase with increasing advance ratio.



(a.) $\alpha = 4.4^{\circ}$, $\mu = 0.15$ **(b.)** $\alpha = 4.9^{\circ}$, $\mu = 0.175$ **(c.)** $\alpha = 5.0^{\circ}$, $\mu = 0.20$

Figure 9 -- BVISPL directivity trend with increasing μ for $C_T = 0.013$.

Airloads

Airloads data for proprotors is extremely limited. Reference 11 reported on experimental measurements for a generic tiltrotor configuration in hover. Several CFD studies have been conducted for hovering tiltrotors (for example, reference 12) to understand the flow mechanisms underlying high thrust conditions. Prior to the TRAM DNW test, there existed no airloads data for proprotor forward-flight operating conditions (either in helicopter- or airplane-modes).

Figure 10a-b is a sample set of sectional pressure coefficient data for the 1/4-scale V-22 rotor in low-speed helicopter-mode forward-flight. The difference between advancing and retreating side rotor pressure coefficient distributions is demonstrated by comparing figures 10a and 10b. The pressure coefficients are nondimensionalized by the local velocity. The individual pressure coefficient distributions in figure 10a-b are all scaled the same.

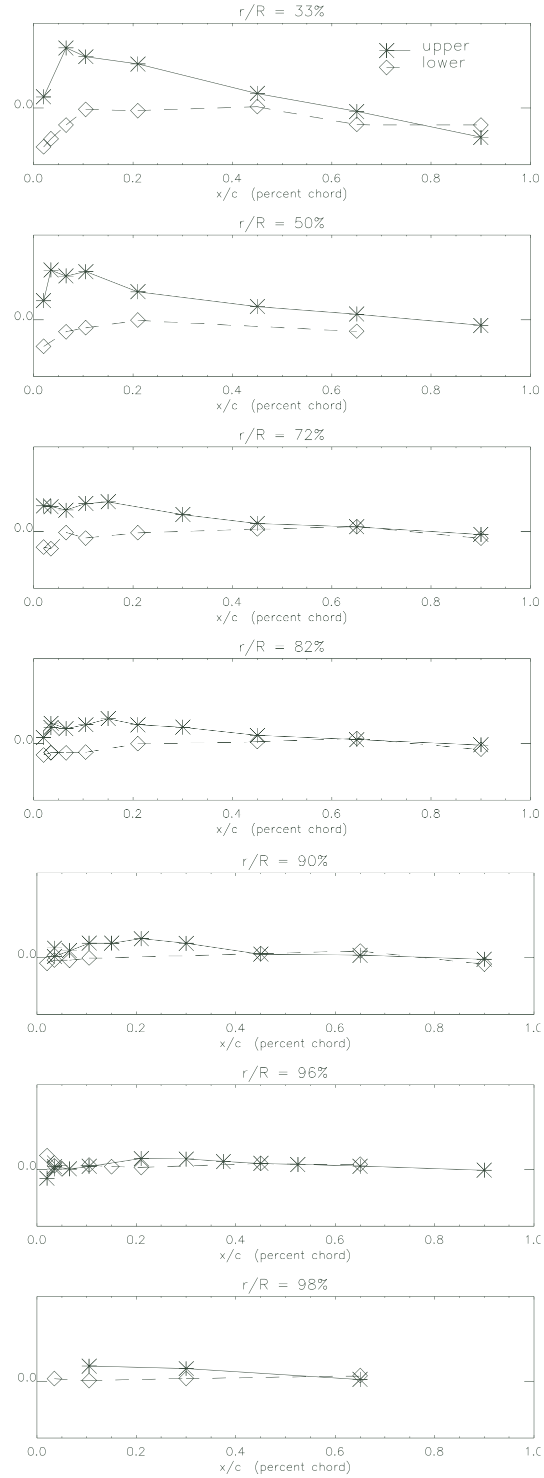


Fig. 10a -- Helicopter-Mode Forward-Flight Sectional Pressure Coefficient Distributions (ψ=90 deg., μ=0.15, C_T=0.009, & α_s= +2 deg.)

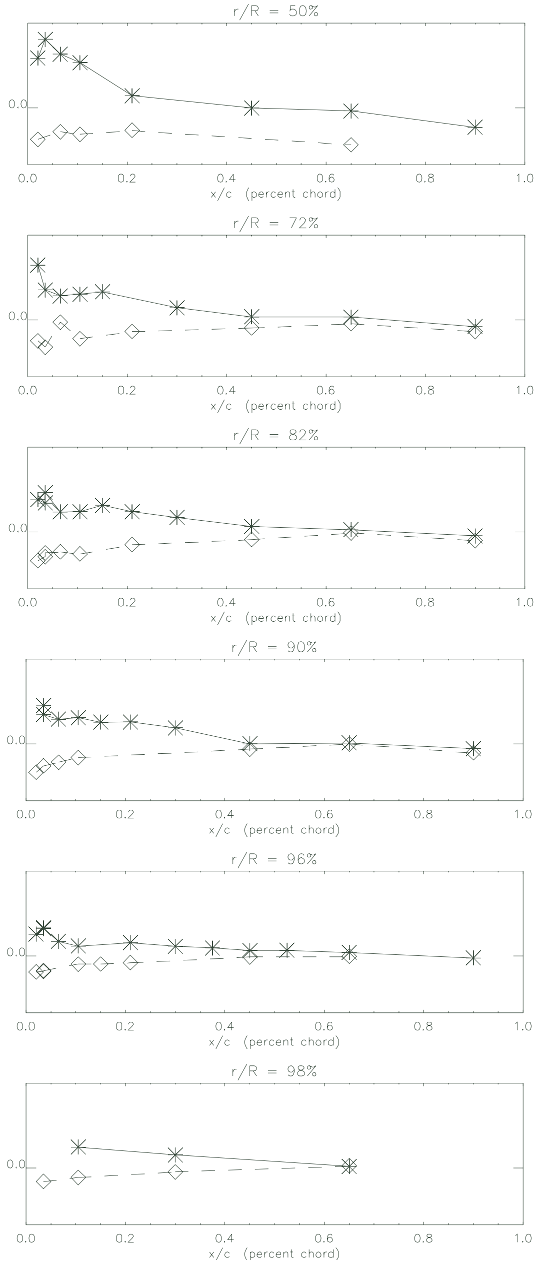


Fig. 10b -- Helicopter-Mode Forward-Flight Sectional Pressure Coefficient Distributions (ψ=270 deg., μ=0.15, C_T=0.009, & α_s= +2 deg.)

Figure 10a is the radial pressure coefficient distribution for the rotor advancing-side (ψ=90 deg.) and figure 10b is the distribution for the rotor retreating side (ψ=270 deg.). The retreating side pressure coefficients are significantly greater in magnitude than the advancing side coefficients – as would be expected for a trimmed rotor in forward-flight.

Figure 10a-b represents a very limited sample of the literally gigabytes of airloads data acquired during the 1/4-scale V-22 isolated rotor test at the DNW. The airloads data will enable new insights into tiltrotor noise mechanisms, will be an important validation data set for a new generation of aeroacoustic prediction tools, and will hopefully inspire new noise reduction strategies for tiltrotor aircraft.

Wake Flow Visualization and Measurements

Both laser-light-sheet (LLS) flow visualization and vortex trajectory measurements were made for the TRAM 1/4-scale V-22 rotor, as well as particle image velocimetry (PIV) vortex velocity measurements. Figure 11 is a representative laser-light sheet flow visualization picture acquired during the DNW test. The rotor blade seen in figure 11 is at ψ=45 degrees and the visible vortices in the figure are on the advancing-side of the rotor.

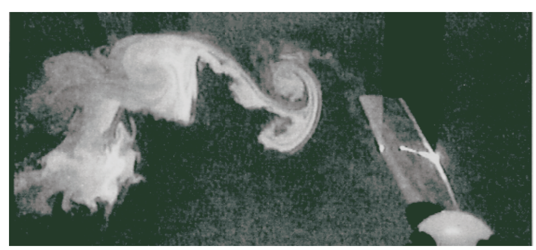


Fig. 11 -- Laser Light Sheet Flow Visualization of Trailed Tip Vortices

Acquisition of a series of laser-light sheet pictures enabled the definition of the three-dimensional vortex filament trajectories for the 1/4-scale V-22 rotor on the advancing-side of the rotor (fig. 12). Both clockwise and counterclockwise vortices were observed in the laser-light sheet pictures. The rotation direction of the observed advancing-side vortices is noted in figure 12.

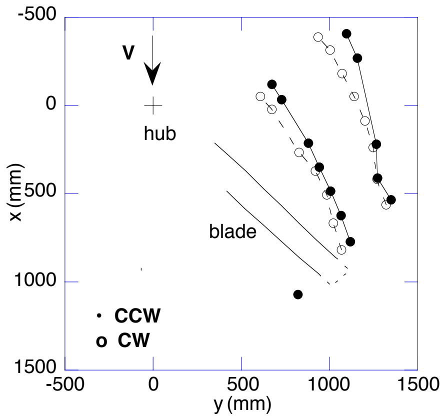


Fig. 12 – Planform View of Vortex Filament Trajectories (Low Thrust, Moderate Positive Rotor Shaft Angle)

Reference 13 presents more detailed findings from the DNW test with respect to the LLS images, the vortex trajectory, and PIV results. One important observation made during the DNW test was the successful imaging of dual rotor vortices being trailed on the advancing side of the proprotor in BVI descent conditions.

Future Plans

Preparations are underway to conduct a test of 1/4-scale V-22 proprotors on the Full-Span TRAM test stand (figure 13) in the National Full-scale Aerodynamics Complex (NFAC) 40-by-80 Foot Wind Tunnel at NASA Ames Research Center.

Fig. 13 -- Full-Span TRAM

Comparison of 1/4-scale V-22 test results from the DNW isolated rotor test and the upcoming NFAC full-span TRAM test will enable assessment of interactional aerodynamic and acoustic effects.

Conclusion

NASA and the U.S. Army have made a major infrastructure investment in tiltrotor test technology through the continuing development of the TRAM. This investment has begun to payoff through acquisition of fundamental aeroacoustic and aeromechanics data from a 1/4-scale V-22 isolated rotor tested in the DNW on the TRAM isolated rotor configuration. The DNW data will enable substantial improvements in the predictive capability for tiltrotor aircraft. This paper has presented an overview of the scope of the data acquired during this experimental investigation. Continuation of in-depth tiltrotor experimental investigations will proceed with tests on a full-span (dual-rotor and complete airframe) TRAM configuration.

Acknowledgements

The experimental results in this paper were derived from research performed under the auspices of the Tilt Rotor Aeroacoustic Model (TRAM) project and the NASA Short Haul Civil Tiltrotor program (SH(CT)). The TRAM and SH(CT) programs are led at NASA Ames Research Center by the Army/NASA Rotorcraft Division and Advanced Tiltrotor Technology Project Office, respectively. Other major funding partners and research participants in the experimental research effort were the U.S. Army Aeroflightdynamics Directorate (AFFD) located at Ames, NASA Langley Research Center Fluid Mechanics and Acoustics Division, and The Boeing Company (Mesa, Arizona). In addition, the outstanding support provided by the Duits-Nederlandse Windtunnel staff during the execution of the wind tunnel test was critical to the success of the test.

The TRAM DNW test team also extends their thanks to the staff of the Dutch Nationaal Lucht- en Ruimtevaartlaboratorium (NLR) and U.S. Army European Research Office (ERO) for their technical and programmatic contributions to the TRAM development and the DNW wind tunnel access, respectively.

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